MODULE 4 PROPERTIES OF MATTER

Elasticity

The property of solids to retain its original size or shape after the removal of deforming force is called **elasticity.** Elasticity can otherwise understand as the ability of some solid material to generate internal force against the deformation force applied externally.

The property of a material to undergo permanent deformation under applied force is called **plasticity.**

The internal reaction force developed inside an elastic material to resist any change in its size or shape is called **restoring force.**

Stress is defined as the internal restoring force developed per unit area in a body

$Stress = \frac{F}{A}$ **unit is N/m^2**

Strain is defined as the ratio of change in dimension to the original dimension of a body.

Strain = Change in dimension/original dimension . It has no units

Elastic limit is the maximum stress that can be applied to the substance before it becomes permanently deformed and does not return to its original state.

Hooke's Law

Hooke's Law states that within elastic limit, the stress is proportional to the strain.

$Stress \,\alpha\, Strain$

$\frac{Stress}{Strain} = a\ const.$ **This constant is called elastic modulus with unit N/m^2**

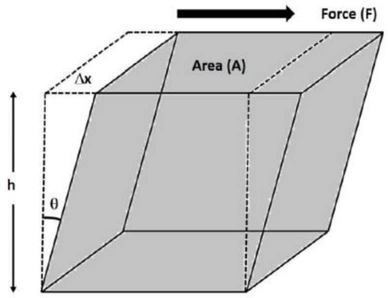
Young's Modulus: Elasticity of Length

It is defined as the ratio of longitudinal stress to the longitudinal strain under relatively small deforming force.

$$Young's\ Modulus = \frac{Longitudinal\ \ stress}{Longitudinal\ \ strain}$$

$$Y = \frac{F/A}{\Delta L/L} = \frac{FL}{A\Delta L}$$

Rigidity Modulus: Elasticity of Shape, is defined as the ratio of shear stress to shear strain



Shearing a rectangular block by applying a force parallel to one of its faces

$$shear\ stress = \frac{tangential\ force}{area} = \frac{F}{A}$$

$$\theta = \frac{arc\ length}{radius} = \frac{\Delta x}{h}$$

$$\therefore\ shear\ strain = \theta$$

$$\eta = \frac{\left(\frac{F}{A}\right)}{\theta}$$

$$\eta = \frac{F}{A\theta}$$

Bulk Modulus: Volume Elasticity

Bulk modulus is the ration of volume stress to volume strain.

$K = \dfrac{F/A}{-\Delta V/V} = P/(-\Delta V/V) = \dfrac{-PV}{\Delta V}$ where P is the Pressure.

The reciprocal of the bulk modulus is called the **compressibility**

Pressure

Pressure (P) is defined as the perpendicular or normal force acting per unit area of a substance. $P = \dfrac{F}{A}$. Pascal is a very small unit of pressure.

Other commonly used units for pressure are $bar = 10^5 Pa$ and $millibar = 100\ Pa$.

Atmospheric Pressure

Atmospheric Pressure is the pressure caused by the Earth's atmosphere (unless you happen to be on another planet).

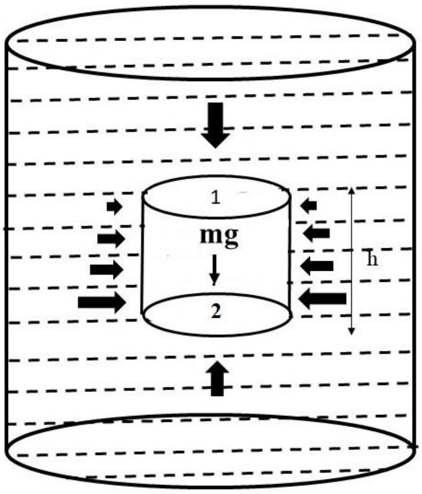
This pressure is commonly affected by altitude, wind velocity, and temperature.

Gauge Pressure and Absolute Pressure

Gauge pressure is the pressure relative to atmospheric pressure. Gauge pressure is positive for pressures above atmospheric pressure, and negative for pressures below it.

Absolute pressure is the sum of gauge pressure and atmospheric pressure.

Absolute pressure uses absolute zero as its zero point, while **gauge pressure uses atmospheric pressure as its zero point.** Due to varying atmospheric pressure, gauge pressure measurement is not precise, while absolute pressure is always definite



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To find the pressure at a depth, consider a fluid at rest in a container. In Figure, point 1 is at height h above point 2. The pressures at points 1 and 2 are P_1 and P_2 respectively. Consider a cylindrical element of fluid having base area A and height h. Since the fluid is at rest the resultant horizontal forces should be zero and the resultant vertical forces should balance the weight of the element. The force acting in the vertical direction are due to the fluid pressure at the top (P_1A) acting downward, at the bottom ($P_2 A$) acting upward.

If mg is the weight of the fluid in the cylinder, then $(P_2 - P_1)A = mg$-----------(1)

Now, if ρ is the mass density of the fluid, we know that $\rho = \frac{m}{V}$ or $m = \rho V = \rho hA$

Hence $(P_2 - P_1)A = \rho hAg$ or $(P_2 - P_1) = \rho hg$

When P_1 may be replaced by atmospheric pressure (P_{atm}) and we replace P_2 by P.
Then the above equation turns to

$(P - P_{atm}) = \rho gh$ or $\boldsymbol{P = P_{atm} + \rho gh}$

Thus, the pressure P, at depth below the surface of a liquid open to the atmosphere is greater than atmospheric pressure by an amount ρgh. This **P is called absolute pressure** at that point.

The excess of pressure,($P - P_{atm}$) at depth, h is called a gauge pressure at that point.
Gauge pressure at a point is the pressure measured relative to the atmospheric pressure.

Blood pressure readings, such as 130/80 mm of Hg, give the maximum and minimum gauge pressures in the arteries, measured in mm Hg or torr. Blood pressure varies with vertical position within the body; the standard reference point is the upper arm, level with the heart.

Surface Tension

The tension of the surface film of a liquid caused by the attraction of the particles in the surface layer by the bulk of the liquid, which tends to minimize surface area

Surface tension is measured in tangential **force per unit length**. Its SI unit is **newton per meter.**

$F \alpha l$ **or** $F = Sl$ **or** $S = \frac{F}{l}$ **where S is the surface tension and its unit is N/m**

Surface energy of the liquid

The extra energy possessed by the surface layer of the liquid is called surface energy (U). Surface energy can be defined as the work done to increase the surface area of the liquid. Surface energy is related to surface tension by the equation,

$surface\ energy = surafce\ tension \times area\ of\ the\ liquid\ surface$

$U = SA$ **or** $S = \frac{U}{A}$

Cohesive force and Adhesive force

Attractive forces acting between molecules of the same type are called ***cohesive forces.***

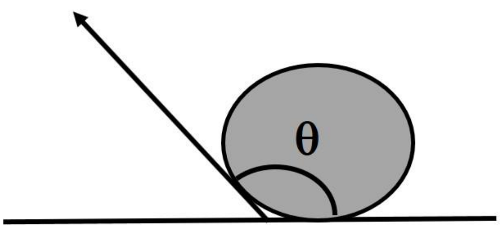
Attractive forces acting between molecules of different types are called ***adhesive forces***. When a liquid comes in contact with a solid surface, the wetting of the surface occurs depending on the ratio of strengths of cohesive and adhesive forces.

When **the adhesive forces dominate,** the surface tension of the liquid becomes low and the liquid spreads over the entire solid surface **(perfect wetting).**

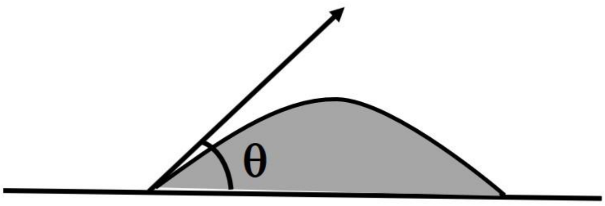
When the **cohesive forces dominate**, the surface tension of the liquid becomes high, and the liquid contracts into drops **(no wetting).**

Angle of contact

The angle between the tangent to the liquid surface at the point of contact and the solid surface inside the liquid is termed the angle of contact.



Obtuse angle of Contact



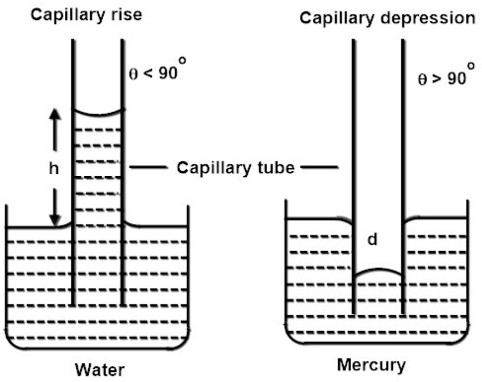
Acute angle of Contact

When cohesive force is larger than adhesive forces, θ >90, (obtuse angle) and the liquid does not wet the solid surface. Eg: water on a waxy or oily surface, on the lotus leaf, and with mercury on any surface.

When adhesive force is larger than cohesive forces, θ <90, (acute angle) and the liquid wet the solid surface. Eg: water or kerosene on glass or plastic or any other surface.

Waterproofing agents or paints used in buildings and other construction actually create a large angle of contact between the water and fibers in it. So, the surface will become hydrophobic in nature.

Capillarity



One of the consequences of surface tension is capillary action or capillarity. When one end of a tube of very small radius (known as capillary tube) is dipped in a liquid, the liquid rises or falls in the tube. This phenomenon is called **capillarity**.

The rise or fall of liquid in the capillary tube depends on the angle of contact between the liquid and the tube.

If the angle of contact is less than 90° (acute angle of contact), the liquid rises in the tube and it is called **capillary rise**.
If the angle of contact is greater than 90° (obtuse angle of contact), the liquid falls in the tube and it is called **capillary depression.**

Ascent Formula

The capillary rise or depression can be found using the formula $h = \frac{2S\cos\theta}{r\rho g}$ where S= surface tension, r =radius of the capillary tube, ρ is the density of the liquid.

Applications of Surface Tension

a) The action of detergents on oil or grease dirt in fabrics

The cleansing action of both soaps and detergents results from their ability to **lower the surface tension of water, to emulsify oil or grease and to hold them in a suspension in water**. This ability is due to the structure of soaps and detergents. The scrubbing action helps in moving the detergent deeper inside the fabric and makes the dirt float on the solution

b) Why do farmers plough the land in the summer season?

In the summer season where water scarcity affects, the farmers plough the land to open up the tiny capillary orifices between the soil. Through these capillaries, the water and air in the bed

c) Effect of temperature and impurities on surface tension

The ***surface tension of a liquid decreases with an increase in the temperature*** of the liquid. This is because cohesive forces decrease with an increase in molecular thermal activity.

FLUID DYNAMICS

Viscosity

Streamline flow and turbulent flow

Streamline flow in fluids is defined as the flow in which the fluids flow in parallel layers such that there is no disruption or intermixing of the layers and at a given point, the velocity of each fluid particle passing by remains constant with time.

At low fluid velocities, there are no turbulent velocity fluctuations and the fluid tends to flow without lateral mixing

The smooth flow of a fluid, with velocity smaller than certain critical velocity (limiting value of velocity), is called streamline flow or laminar flow of a fluid.

The irregular and unsteady flow of a fluid when its velocity increases beyond critical velocity are called turbulent flow.

turbulent flow, **type of fluid (gas or liquid) flow in which the fluid undergoes irregular fluctuations, or mixing**, in contrast to laminar flow, in which the fluid moves in smooth paths or layers. In turbulent flow the speed of the fluid at a point is continuously undergoing changes in both magnitude and direction.

What is a Reynolds Number?

Reynolds number is a dimensionless quantity that is used to determine the type of flow pattern as laminar or turbulent while flowing through a pipe.

Reynolds number is defined by the ratio of inertial forces to that of viscous forces.

$R_e = \frac{initial\ force}{viscous force}$ or $R_e = \frac{\rho v d}{\eta}$ where ρ is the density of the fluid, v is the velocity of the flow, d is the diameter of the pipe and η is the coeft of viscosity of the fluid

It is found that flow is streamline or laminar for *Re* less than 1000.
The flow becomes unsteady for *Re* between 1000 and 2000.
The flow is turbulent for *Re* greater than 2000.

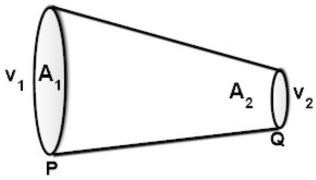
Equation of Continuity (Law of conservation of Mass)

When an incompressible, non-viscous fluid flows steadily through a tube of non-uniform cross section, then the product of the area of cross section and the velocity of the flow is same every point in the tube.

The product of area and velocity gives flow rate. This is expressed in the **Continuity Equation**:

$Q = Av = a\ const.$ or $A_1v_1 = A_2v_2$

where A1 and A2 are areas of cross section at two different points 1 and 2 and v1 and v2 are the velocities at that points



Proof

Consider the figure above. At the initial point P, let the velocity of the fluid be v_1 and area of cross section be A_1. At the point Q, let the velocity of the fluid be v_2 and area of cross-section be A_2.

If ρ is the density of the fluid and considering the flow of fluid through the pipe for a time t,

Mass of the fluid entering the tube at point P = $\rho A_1v_1\Delta t$ (density x volume)

Mass of the fluid entering the tube at point Q = $\rho A_2v_2\Delta t$

At steady state, the total mass of the fluid entering into a pipe through any cross-section should be equal to the total mass of fluid coming out of the same pipe through any other cross-section at the same time.

Hence $\rho A_1v_1\Delta t = \rho A_2v_2\Delta t$ $\quad$ $A_1v_1 = A_2v_2$ or ***$Av = constant$***

The product Av, which has the dimensions of volume per unit time, is called either the volume flux or **the flow rate.**

Energies of a flowing fluid

A flowing fluid possesses three types of energies - kinetic energy, potential energy, and pressure energy

If *m* mass of the fluid flows with a velocity *v*, then kinetic energy is given by

$$Kinetic Energy = \frac{1}{2}mv^2$$

The energy of the fluid by virtue of its position is called potential energy

$$Potential\ Energy = mgh$$

Pressure energy due to the action of fluid molecules to any substance immersed. Is called Pressure energy. If P is the pressure, m is the mass of fluid and ρ is the density of the fluid, the pressure energy is given by

$$\Pr essure energy = \frac{mP}{\rho}$$

Bernoulli's Theorem

Bernoulli's theorem is **analogous to the law of conservation of energy in Mechanics** and is derived by applying the work-energy theorem to the fluid in a section of a flow tube.

Bernoulli's theorem states that the sum of kinetic energy, potential energy, and pressure energy of an ideal fluid in a streamline flow remains constant throughout the flow.

By work-energy theorem at two sections of a pipe with different heights h_1 and h_2 and v_1 and v_2 are the velocities of flow with pressure P_1 and P_2, That is, we can write,

$$(P_1 - P_2)V = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 + mgh_2 + mgh_1$$

For unit volume,

$$(P_1 - P_2) = \frac{1}{2}\rho v_2^2 - \frac{1}{2}\rho v_1^2 + \rho gh_2 + \rho gh_1$$

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho gh_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho gh_2 \qquad \text{or} \qquad P + \frac{1}{2}\rho v + \rho gh = a\,const.$$

That is ***pressure energy + kinetic energy + potential energy = constant***

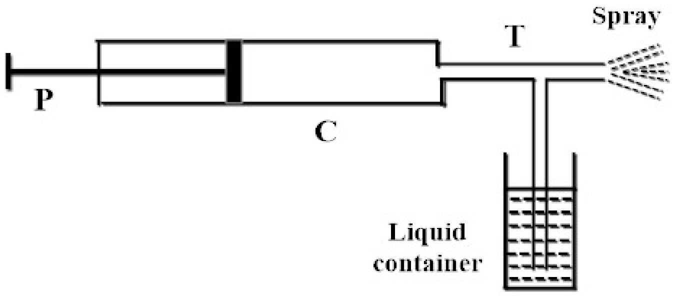
The work done on a unit volume of fluid by the surrounding fluid is equal to the sum of the changes in kinetic and potential energies per unit volume that occur during the flow.

Applications of Bernoulli's theorem

a) Atomizer

An atomizer is a device to spray a liquid or make a liquid into a jet of tiny droplets., like in body spray, spray painting, car wash stations, etc.

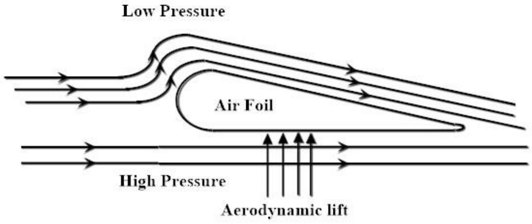
The principle behind the working of atomizers is Bernoullis theorem. According to Bernoulli's theorem, the velocity of a fluid increases in a region, the pressure decreases in that region, and vice versa in order to maintain the total energy as constant.



According to Bernoulli's theorem, the pressure in the T section pipe must be lower than the pressure at the surface of the liquid in the container. Because of this pressure difference, the liquid in the container rises up and reaches the T junction pipe. The liquid mixes with high-speed air to form a spray.

For a perfume bottle or spray paint, the container with liquid is kept at high pressure with an air compressor. So, a small pressure difference created due to the press at the spray piston will give a jet of liquid particle or atomized liquid.

b) Airfoil



Airfoil is a special shape of solid objects which produces a lifting effect or floating effect while moving in a streamlined fluid or air. The cross-section of wings of an airplane, boomerang, wings of birds, propeller blade, turbine blade, etc possess an airfoil shape

When the airfoil is moving against the streamlined air, because of this special shape the streamlines might have a speed difference at the upper and lower surfaces. If the air streams are moving at different speeds, so with different kinetic energy, then according to Bernoulli's theorem there will be pressure difference. The pressure energy should be lesser at the upper side of the airfoil than on the lower side which introduces a lifting force from the lower side of the airfoil that tries to float the airfoil while it is in motion.

VISCOSITY

The property of a fluid by virtue of which it tends to resist the relative motion between the layers of the fluid is called viscosity.
The viscous force (F) acting between two layers of the liquid is directly proportional to the area of liquid layers and the velocity gradient between the layers (v_2 - v_1 / d).
Combining these proportionalities, we can write,

$$F \alpha A \frac{(v_2 - v_1)}{d} \quad \text{or} \quad F = \eta A \frac{(v_2 - v_1)}{d}$$

The constant of proportionality η is called the coefficient of viscosity of the fluid.

Therefore, **the co-efficient of viscosity η** can be defined as that much resistive force developed between the liquid layers of unit area when they are moving with a unit velocity gradient. The SI unit of coefficient of viscosity η is $kgm^{-1}s^{-1}$ or Nsm^{-2}.

Terminal velocity

Terminal velocity is defined as **the highest velocity attained by an object falling through a fluid**. It is observed when the sum of drag force and buoyancy is equal to the downward gravity force acting on the object. When the body attains terminal velocity, the acceleration of the object is zero as the net force acting on the object is zero.

Stoke's law

Stokes Law gives the relation between the velocity and frictional force acting on a spherical body moving in a viscous fluid.

The viscous drag force acting on a body as it passes through a viscous fluid is directly proportional to the sphere's velocity, radius, and fluid viscosity. This is Stokes law.

This equation of Stokes Law can be given as, **$F = 6\pi\eta r v$** where η is the coefficient of viscosity, **r** is the radius of the spherical body, v is the sphere's velocity.